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METAMORPHIC STUDIES

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INTRODUCTION

The early study of rock metamorphism consisted principally in the aggregation of a vast mass of more or less unrelated observations on rock alterations. Much of the literature on metamorphism has been so technical and so purely descriptive that it is natural that the general reader tends to postpone serious consideration of the subject. In recent years notable attempts by Van Hise,[1] Grubenmann,[2] and others have been made toward systematizing the subject and making it more available. Their works, especially that of Van Hise, are epoch-making and must necessarily be in the hands of the student of metamorphism. Later study has been more along quantitative lines and has resulted, as would be expected, in clarifying some of the principles, and in a better understanding of their significance. There seems to be need now of a more elementary treatment of metamorphism, shorn of some of the less essential details, and including recent quantitative developments which would be more widely used were their significance understood. This series of articles is an attempt to meet this need. Quantitative results, usually expressed graphically, will be used as a basis for the development of the principles of metamorphism. In the first article the general significance of the metamorphic cycle is discussed, as preliminary to a more detailed consideration of metamorphism.

THE METAMORPHIC CYCLE DESCRIBED[3]

The keynote of rock alterations is adaptation to environment. A molten rock or magma enters the outer shell of the earth and comes within our range of observation. No sooner does it crystallize than changes begin—with great rapidity nearest the surface, with less rapidity below. These changes are both chemical and physical. Water, carbon dioxide, oxygen, and other substances of the hydrosphere and atmosphere attack the rocks. The ferrous iron of the igneous rocks combines with oxygen and water and a large part of it remains as residual limonite. Alkalies and alkaline earths form soluble salts and are leached out in well-determined order. Free quartz is less readily changed or dissolved. The portions of the bases which the waters have failed to abstract tend to remain combined with alumina and silica, taking on water to form new hydrous silicates, although some of them may remain in place as carbonates or other salts. The excess of alumina and silica left from the leaching out of the bases from silicates becomes hydrated and forms clay. There are ultimately left, then, iron oxide, quartz, clay, and a variety of hydrous aluminum silicates, characterized by a lower ratio of silica to the bases than in the original silicate minerals. Oxide zones of ore deposits are special cases of these residual products. These substances on the erosion surface are mechanically distributed and ultimately become segregated as mud and sand, or even iron ores. The substances which are taken out in solution may remain in solution in the sea or may be redeposited as limestone, dolomite, chert, iron carbonate, or iron silicate—in other words, as chemical sediments. Part of these substances also may be deposited as cements. The ultimate results of the destruction of the original igneous rocks, then, are the sediments, the oceanic salts, and the non-transported residual products of rock decay.

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[1] C. R. Van Hise, *A Treatise on Metamorphism*, Mono. 47, U.S. Geological Survey, 1903, pp. 1286.

[2] Dr. U. Grubenmann, *Die kristallinen Schiefer*, Part I, 1904; Part II, 1907. Berlin.

[3] C. K. Leith, "The Metamorphic Cycle," *Journal of Geology*, XV (1907), 303–13.

The changes above outlined involve the addition of substances of light molecular weight, such as carbon dioxide, water, and oxygen. In terms of elements oxygen is of dominant importance. The resulting minerals are on the whole of simpler molecular composition and of lower specific gravity. The actual addition of new substances has also increased volume. The unconsolidated products have a large pore space which still further increases the volume of the mass. Energy is released in an enormous amount. It has been calculated that a gram of average igneous rock releases on complete decomposition at least 120 calories of heat.

This change was called katamorphism by Van Hise. By katamorphism the rock tends to become adapted to a surface environment. The resulting product may be compared to a solution, both solid and liquid, of the original rock substances and the atmosphere and hydrosphere.

But there is ever present a reverse or anamorphic tendency which has maximum effectiveness in producing results in proportion as the substances on which it works have suffered katamorphism. Its effects are conspicuous on the sediments; they are much less conspicuous on igneous or crystalline rocks. No sooner have sediments been deposited than they tend to become consolidated by settling and by infiltration of cements. This process of induration is aided by the pressure of the accumulating sediments, and as this pressure due to burial increases, other changes take place. The substances which had been added in katamorphism are forced out: first the water, then carbon dioxide, ultimately oxygen. The bases are recombined with the alumina and silica to reproduce some of the silicates of the original rock; not all of the silicates, however, for certain of the bases have been carried to the sea where they remain in solution, and thus the original ratios of bases to alumina and silica cannot be reproduced without the addition of bases from without. The mineral molecules are on the whole more complex. Volume decreases by elimination of pore space, by elimination of substances, by new molecular groupings of higher density. A schistose or slaty structure is developed. Energy is absorbed. In proportion as the rocks are buried by the load of overlying sediments or in proportion as they suffer mechanical deformation or contact metamorphism these anamorphic changes are expedited. The changes tend in general to make the rocks approach the igneous rocks in mineral and chemical composition.

The succession of katamorphic and anamorphic changes above outlined constitutes the metamorphic cycle. It is not necessary to assume that all rocks undergo this cycle. The cycle may be changed to a reverse phase at any point, but the tendency is the same. The recurrence of cycles of the type above described constitutes great earth pulsations. The movement is in one sense oscillatory. Van Hise has used the term "zone of katamorphism" for the region near the surface where katamorphic processes are at a maximum and the "zone of anamorphism" for a deeper region where the reverse changes are at a maximum; thus emphasizing influence of depth on metamorphic changes. These terms are extremely useful in the general sense in which Van Hise used them. It is difficult, however, to use them in the inductive study of rock changes, for so may other factors enter that at any depth the changes may be in opposite directions for different kinds of rocks or for the same rock at different times. The conception of the metamorphic cycle is better adapted to an inductive study of the rocks, for it relates merely to the succession of changes in the rock without reference to depth.

INFERENCES AS TO SIGNIFICANCE OF CYCLE

It is not enough merely to have established the existence of these cycles. We are interested in knowing the total energy changes involved, what keeps the cycle going, whether the cycle is closed, the net results in distribution of rock substances.

ENERGY CHANGES INVOLVED IN THE CYCLE

Much remains to be learned about the energy changes in common rock alterations, but enough is quantitatively known to enable us to state, with some confidence, that the changes of the metamorphic cycle result in a permanent net loss of energy from the system in the form of heat. It may be assumed from this and from a priori reasoning that it is this running down of energy which keeps the cycle going. In the igneous rocks energy is locked up in the molecular combination of minerals which under katamorphism is liberated as heat and much of it permanently lost. As this change involves expansion, it is constantly opposed by gravity, while in the anamorphic phase of the cycle gravity controls, leading to a diminution of volume. We may suppose that at any given depth some sort of energy equilibrium exists between pressure and the energy locked up in molecular combinations. So far as a rock is not adapted to this state of equilibrium, changes will go on. A granite formed under conditions of high temperature and high pressure when brought to the surface finds itself under conditions of low temperature and low pressure. The expansive forces of the chemical reactions with the surface elements or expansive forces mechanically locked up in crystalline structure are but feebly resisted by gravity. The rock adapts itself to the new conditions of equilibrium. Unconsolidated sediments, when buried beneath the surface, reach new conditions of temperature and pressure, and readjustment is required to establish a condition of energy equilibrium. The constituents of the sediments are forced together by gravity, and energy is locked up in the molecular combinations, only to be lost again as the rock later comes under katamorphic conditions.

If heat is permanently lost by the pulsational or cyclic changes, while gravity remains constant, it may be supposed that the energy available for rock change at a given depth becomes lower. In order that the rock may fully complete its cycle by storing up energy in one phase equal to that lost in another it must go to a point deeper within the earth, where increased effect of pressure can make up for the loss of heat during the cycle. The running down of energy therefore implies the permanent accumulation of metamorphic products instead of reproducing igneous rocks on the original scale.

The probable incompleteness of the metamorphic cycle, as inferred from energy changes, is more satisfactorily indicated by field evidence to be noted below.

GEOLOGICAL EVIDENCE THAT CYCLE IS NOT CLOSED

1. *Subcrustal fusion.*—Completion of the cycle would involve reproduction of igneous rocks from sediments wherever they have reached sufficient depth—so-called subcrustal fusion. So far as observation goes, the common results of anamorphism are schists and gneisses characterized by greater abundance of platy and columnar minerals than the original igneous rocks. Locally, near igneous contacts, anamorphism reproduces rocks indistinguishable from the original igneous rocks. We do not attempt to show that subcrustal fusion has not occurred on some scale, but believe that there is no adequate evidence within our zone of observation that this has been accomplished on a large enough scale to complete the metamorphic cycle for anything but a small proportion of metamorphosed rocks. The lowest known rocks of the geological

column, the Keewatin rocks of Lake Superior, are for the most part fresh basalts with minor quantities of sediments which certainly have not been liquefied, notwithstanding the fact that they have been buried to maximum depths known to our observation. The great Laurentian batholiths of granite intruding the Keewatin and lower portions of the Huronian sediments have been regarded as the fused lower beds of the Huronian series fused by reason of depth of burial. And yet when these same Huronian sediments are followed out they are found in some adjacent areas to rest unconformably, with basal conglomerate, on an old basement of granite or Keewatin green schists with no signs of fusion. This depth has not been sufficient to cause fusion. The extreme of anamorphism shown is a schistose structure resulting from rock flowage in part of these rocks. It is known both by field and experimental observation that rock flowage producing schistosity does not require fusion. Adams[1] has shown experimentally that even to depths greater than 12 miles the weight of overlying rocks alone is not sufficient to close cavities—much less liquefy the rock. The only evidences for fusion are around the peripheries of intrusive igneous rocks. These intrusions are, on the scale of the earth, relatively insignificant masses, which have worked their way upward from a much deeper zone, carrying up energy necessary for the fusion.

In short, the metamorphic cycle within our zone of observation has usually not been completed. Since Keewatin time at least, the cycle has resulted in the gradual accumulation of sediments and their equivalent schists. Some small parts have been reconverted to igneous rocks around igneous intrusions. Whether beneath the Keewatin, sediments have been more largely converted into igneous rocks, we have no means of knowing. It may be that the span of time between the Keewatin and the present represents too small a part of the geological record from which to drawn inferences, but it is all we have as a basis of observation.

2. *Salts of the sea.*—Certain salts split off from the cycle and remain in the ocean. The salinity of the sea has been regarded as continuously increasing since the beginning of geological time.

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[1] *Journal of Geology*, XX (1912), 97–118.

This cumulative extraction of salts must have an effect ultimately on the composition of the rocks of the shell, though perhaps so slight and so minutely distributed through a great mass of rocks that there is little hope of measuring it.

3. *Limestone.*—Another cumulative segregation accompanying the metamorphic cycle which has come to be recognized only recently is the segregation of lime near the earth's surface. As we follow carefully and quantitatively the anamorphic changes of all kinds of rocks, the fact stands out conspicuously that excess of lime is expelled by anamorphism. The schists and gneisses characteristic of anamorphism contain a minimum of lime carbonate or even of lime silicates. To only a very limited extent lime enters into the constitution of platy or columnar minerals adapted to the anamorphic state. This expulsion of lime in anamorphism suggests a concentration of the lime near the surface. This is further suggested by another fact. It may be easily calculated what proportion of limestone to other sediments could be expected from the breaking down of igneous and crystalline rocks of average chemical composition, and on various calculations this has been found to range from 5 to 12 per cent. It is impossible to state exactly the actual proportion of limestone to other sediments in our zone of observation, but the available facts point to a much higher percentage of limestone, anywhere from 25 to 50 per cent. It might be objected to this argument that limestones tend to become localized on continental areas with corresponding deficiency in oceanic basins, beyond our direct zone of observation. This is entirely possible but so far as facts are available from dredging, or from computations from the rate of deposition of deep-sea deposits, there does not seem to be this compensating deficiency.

4. *Dolomites.*—Dolomites seem to be more abundant in older and more highly metamorphosed geological terranes than in later ones. As the detailed changes of the metamorphic cycle are followed, we find that magnesia persists through the cycle to a much larger extent than lime, as attested by actual analyses of related series of specimens. The recurrence of cycles should lead to an increased percentage of lime over magnesia in the great carbonate formations. That limestones are in larger proportion to

dolomite in later as compared with earlier formations seems to be a pretty well-established fact. If it is true, it supports our inference of the progressive accumulation of limestone near the earth's surface.

5. *Alumina and silica the carriers.*—We are beginning to think of the cycle as one which is traveled through principally by alumina and silica; that these substances act as buckets which carry out toward the surface the bases in different relative proportions. The lime and soda are not carried back to a large extent. The potassa and magnesia are carried back to a larger extent. Iron, so far as we know, is carried pretty well through. Water and carbon dioxide in katamorphism are the effective agents in breaking up the combinations of the alumina and silica and thereby unloading the buckets. In the anamorphic phase of the cycle, the water goes down in the otherwise empty buckets in combination with alumina and silica as clay, but only for a short distance, because the hydrates are not adapted to the conditions of pressure below. Alumina and silica are not only redistributing substances, but by their combinations are the carriers and distributors of the energy involved in the changes.

CONCLUSION

In summary, then, the metamorphic cycle may be regarded as indicative of a great pulsational alteration of the earth's surface, kept going through the running down of energy and its escape from the earth, the cycle being an expression and vehicle of this running down of energy. This cycle involves reversals of processes which keep the rock materials within certain limits of mineral condition and distribution, but these reversals are not quite compensating, with the result that there is a residual accumulation and redistribution of certain substances such as sediments, schists, and gneisses, and salts of the sea. Some of the accumulations are definitely known, some are inherently probable, some are merely suspected.

If there is truth in this general conception of the net results of metamorphic cycles, the study of metamorphism may become somewhat prognostic if we use it to direct our search for some of these larger cumulative results which are now obvious in detailed work.

The discernment of these results will require a much wider range of study and quantitative observation than we have before attempted.

The acceptance of this view of the significance of the metamorphic cycle involves perhaps a slight modification of the prevalent interpretation of Hutton's great law of uniformitarianism, that the present is the key to the past. In metamorphism the same series of processes are operating today that have operated in the past, but they have slowly made over the rock types and redistributed them vertically and horizontally, with the result that while the same processes act today as have acted in the past, they are today operating, we infer, on different proportions and distributions of substances, with consequently differing emphasis and producing slightly different results.